CDF note 11080

Final combination of the CDF results on top-quark mass

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We summarize the top-quark mass measurements from the CDF experiments at Fermilab. We combine published Run I (1992–1996) measurements with the most precise Run II (2001–2011) measurements based on data sets corresponding to $8.7 - 9.3$ fb^{-1} of $p\bar{p}$ collisions. Taking correlations of the uncertainties into account, and combining the statistical and systematic uncertainties, the resulting preliminary CDF average mass of the top quark is $M_{\rm t} = 173.16 \pm 0.93$ GeV/c^2, corresponding to a relative precision of 0.54%.

I. INTRODUCTION

This note reports on the final combination of the CDF top-quark mass measurements. The combination includes results from the CDF run at 1.8 TeV center of mass collision energy (Run I), analyzing 0.1 fb^{-1} of data [1–6]. The Run I measurements are combined with three recently published [7–9] and two preliminary results [10, 11]. The latter analyses uses the full Run II samples of $8.7-9.3\,\mathrm{fb}^{-1}$ of data collected with the CDF II detector. This analysis is an update of the combined CDF top-quark mass reported in [12] and the result reported in the combined Tevatron top-quark mass paper [13]. The most accurate CDF Run II published measuremenrs were used in the recent world combination of the top-quark mass, which combines measurements from Tevatron (CDF and D0) and LHC (ATLAS and CMS) experiments [14].

The CDF collaboration has performed many direct measurements of the top-quark mass (M_{t}) using data collected at the Tevatron proton-antiproton collider. The pioneering measurements were collected in the Run I period (from 1992 to 1996) [2, 3, 6], and included results from the decay channels $t\bar{t} \to W^+bW^-\bar{b} \to \ell\nu bqq'\bar{b}$ (ℓ+jets),$t\bar{t} \to W^+bW^-\bar{b} \to qq'bqq'\bar{b}$ (alljets), and $t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$ ($\ell\ell$), where $\ell = e$ or μ. Decays with $\tau \to e, \mu$ are included in the direct $W \to e$ and $W \to \mu$ channels.

In Run II (2001–2011), many precise top-quark mass measurements have been performed, and those considered here are the final results in the different decay channels. Comparing to Run I, a new analysis using $\not\!\!E_T$ plus 3 and more jets was added [8]. The results from these analyses are based on total Run II luminosities of $8.7-9.3$ fb^{-1} of data [7, 8, 10, 11]. Additionally in Run II, CDF performed an analysis based upon charged particle tracking for exploiting the transverse decay length of b-tagged jets (L_{XY}) and the transverse momentum of electrons and muons from W boson decays (p_T^{lep}) [9]. This analysis uses a partial data set corresponding to a luminosity of 1.9 fb^{-1}, and there are no plans to update this analysis.

With respect to the Winter 2013 Tevatron combination [13] and the published version of the combination [15], the Run II CDF measurement in the $\ell\ell$ and alljets channels have been updated using 9.0 fb^{-1} and 9.3 fb^{-1} of data, respectively. The published Run II measurements in the ℓ+jets channel [7], and missing transverse energy plus jets ($\not\!\!E_T$+jets, MET) channel [8] are unchanged. The measurement based on charged particle tracking [9] was incorporated as described in the past combination [16].

This combination supersedes any previous combined CDF top mass value from the CDF and Tevatron combinations [13, 15, 16] and earlier.

The definition and evaluation of the systematic uncertainties and the understanding of the correlations among channels and CDF runs is based on the outcome of many years of work of the Tevatron and LHC top groups and is described in detail elsewhere [14, 15].

The input measurements and uncertainty categories used in the combination are detailed in Sections II and III, respectively. The correlations assumed in the combination are discussed in Section IV and the resulting CDF top-quark mass is given in Section V. A summary is presented in Section VI.

II. INPUT MEASUREMENTS

Eight measurements of M_{t} used in this combination are shown in Table I. The Run I measurements all have relatively large statistical uncertainties and their systematic uncertainties are dominated by the total jet energy scale (JES) uncertainty. In Run II CDF takes advantage of the larger $t\bar{t}$ samples available and employs new analysis techniques to reduce both of these uncertainties. In particular, the Run II CDF analyses in the ℓ+jets, alljets and $\not\!\!E_T$+jets channels constrain the response of light-quark jets using the kinematic information

Table I: Summary of the measurements used to determine the CDF combination of M_t. Integrated luminosity ($\int \mathcal{L}\,dt$) has units of fb^{-1}, and all other numbers are in GeV/c^2. The uncertainty categories and their correlations are described in Section III. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature. "n/a" stands for "not applicable", "n/e" for "not evaluated".

CDF Preliminary
(All uncertainies are in GeV/c^2)

	Run I published			Run II published			Run II preliminary	
	ℓ+jets	$\ell\ell$	alljets	ℓ+jets	Lxy	MET	$\ell\ell$	alljets
$\int \mathcal{L}\,dt$ [fb^{-1}]	0.1	0.1	0.1	8.7	1.9	8.7	9.0	9.3
Top-quark mass [GeV/c^2]	176.1	167.4	186.0	172.85	166.90	173.93	170.80	175.07
In situ light-jet calibration (iJES)	n/a	n/a	n/a	0.49	n/a	1.05	n/a	0.97
Response to $b/q/g$ jets (aJES)	n/a	n/a	n/a	0.09	n/a	0.10	0.18	0.02
Model for b jets (bJES)	0.6	0.8	0.6	0.16	n/a	0.17	0.28	0.20
Out-of-cone correction (cJES)	2.7	2.6	3.0	0.21	0.36	0.18	1.65	0.37
Light-jet response (2) (dJES)	0.7	0.6	0.3	0.07	0.06	0.04	0.46	0.09
Light-jet response (1) (rJES)	3.4	2.7	4.0	0.48	0.24	0.40	1.72	0.42
Lepton modeling (LepPt)	n/e	n/e	n/e	0.03	n/a	n/a	0.36	n/a
Signal modeling (Signal)	2.6	2.9	2.0	0.61	0.90	0.63	0.96	0.53
b-tag modeling (btag)	0.0	0.4	0.0	0.03	0.0	0.03	0.05	0.04
Background from theory (BGMC)	1.3	0.3	1.7	0.12	0.80	0.00	0.03	0.00
Background based on data (BGData)	0.0	0.0	0.0	0.16	0.20	0.15	0.35	0.15
Calibration method (Method)	0.0	0.7	0.6	0.05	2.50	0.21	0.19	0.87
Multiple interactions model (MHI)	n/e	n/e	n/e	0.07	0.00	0.18	0.30	0.22
Systematic uncertainty (Syst)	5.3	4.9	5.7	0.98	2.90	1.35	2.69	1.56
Statistical uncertainty (Stat)	5.1	10.3	10.0	0.52	9.00	1.26	1.83	1.19
Top-quark mass uncertainty	7.3	11.4	11.5	1.11	9.46	1.85	3.25	1.96

from $W \to qq'$ decays (so-called *In situ* calibration) [17]. Residual JES uncertainties associated with p_T and η dependencies as well as uncertainties specific to the response of b jets are treated separately.

Table I lists the individual uncertainties of each result, subdivided into the categories described in the next Section.

III. UNCERTAINTY CATEGORIES

We employ the same uncertainty categories, which are used in the previous Tevatron combination [13]. They are divided such that sources of systematic uncertainty that share the same or similar origin are combined as explained in Ref. [15].

Some systematic uncertainties have been separated into multiple categories to accommodate specific types of correlations. For example, the jet energy scale (JES) uncertainty is subdivided into six components to more accurately accommodate our best understanding of the relevant correlations between input measurements.

For this note we use the newnaming scheme described in Ref. [15]. In parentheses, the old names of the systematic uncertainties are provided. There is a one-to-one matching between the new and old systematic definitions of categories.

Statistical uncertainty (Statistics): The statistical uncertainty associated with the M_{t} determination.

***In situ* light-jet calibration (iJES):** This is a part of the JES uncertainty that originates from *In situ* calibration procedures and is uncorrelated among the measurements. In the combination reported here, it corresponds to the statistical uncertainty associated with the JES determination using the $W \to qq'$ invariant mass in the CDF Run II ℓ+jets, alljets, and MET measurements.

Response to $b/q/g$ jets (aJES): That part of the JES uncertainty that originates from average differences in detector electromagnetic over hadronic (e/h) response for hadrons produced in the fragmentation of b-jets and light-quark jets.

Model for b jets (bJES): That part of the JES uncertainty that originates from uncertainties specific to the modeling of b jets and that is correlated across all measurements. This includes uncertainties arising from variations in the semileptonic branching fractions, b-fragmentation modeling, and differences in the color flow between b-quark jets and light-quark jets. These were determined from Run II studies but back-propagated to the Run I measurements, whose *Light-jet response (1)* uncertainties (*rJES*, see below) were then corrected to keep the total JES uncertainty constant.

Out-of-cone correction (cJES): That part of the JES uncertainty that originates from modeling uncertainties correlated across all measurements. It specifically includes the modeling uncertainties associated with light-quark fragmentation and out-of-cone corrections.

Light-jet response (1) (rJES): The remaining part of the JES uncertainty that covers the absolute calibration for CDF's Run I and Run II measurements. It also includes small contributions from the uncertainties associated with modeling multiple interactions within a single bunch crossing and corrections for the underlying event.

Light-jet response (2) (dJES): For CDF, this uncertainty term includes only the small relative response calibration (η-dependent) for Run I and Run II.

Lepton modeling (LepPt): The systematic uncertainty arising from uncertainties in the scale of lepton transverse momentum measurements. It was not considered as a source of systematic uncertainty in the Run I measurements.

Signal modeling (Signal): The systematic uncertainty arising from uncertainties in $t\bar{t}$ modeling that is correlated across all measurements. This includes uncertainties from variations of the amount of initial and final state radiation and from the choice of parton distribution function used to generate the $t\bar{t}$ Monte Carlo samples that calibrate each method. It also includes the uncertainty from higher-order corrections evaluated from a comparison of $t\bar{t}$ samples generated by MC@NLO [18] and HERWIG [19] or POWHEG

[20] and PYTHIA [21]. Additionally, the systematic uncertainty arising from a variation of the phenomenological description of color reconnection (CR) between final state particles [22, 23] is included in the *Signal modeling* category. This uncertainty was not evaluated in Run I since the Monte Carlo generators available at that time did not allow for variations of the CR model. These measurements therefore do not include this source of systematic uncertainty. Finally, the systematic uncertainty associated with the hadronization model is added. It includes variations observed when substituting PYTHIA [21, 24, 25] for HERWIG [19, 26] when modeling the $t\bar{t}$ signal.

b-tag modeling (btag): This is the part of the uncertainty related to the modelling of the b-tagging efficiency and the light-quark jet rejection factors in the MC simulation with respect to the data.

Background based on data (BGData): This includes uncertainties associated with the modeling using data of the QCD multijet background in the alljets, MET, and ℓ+jets channels and the Drell-Yan background in the $\ell\ell$ channel. This part is uncorrelated between experiments.

Background from theory (BGMC): This systematic uncertainty on the background originating from theory (MC) takes into account the uncertainty in modeling the background sources. It is correlated between all measurements in the same channel, and includes uncertainties on the background composition, normalization, and shape of different components, e.g., the uncertainties from the modeling of the W+jets background in the ℓ+jets channel associated with variations of the factorization scale used to simulate W+jets events.

Calibration method (Method): The systematic uncertainty arising from any source specific to a particular fit method, including the finite Monte Carlo statistics available to calibrate each method.

Multiple interactions model (MHI): The systematic uncertainty arising from a mismodeling of the distribution of the number of collisions per bunch crossing owing to the steady increase in the collider instantaneous luminosity during data-taking. This uncertainty has been separated from other sources to account for the fact that it is uncorrelated between experiments.

These categories represent the final CDF understanding of the various sources of uncertainty. We do not expect these to evolve in the future.

IV. CORRELATIONS

The following correlations are used for the combination:

- The uncertainties in the *Statistical (Stat)*, the *In situ light-jet calibration (iJES)*, and *Calibration method (Method)* categories are taken to be uncorrelated among the measurements.
- The uncertainties in the *Response to b/q/g jets (aJES)*, *Light-jet response (2) (dJES)*, *Lepton modeling (LepPt)*, *Multiple interactions model (MHI)* and *b-tag modeling (btag)* categories are taken to be 100% correlated among all Run I and all Run II measurements, but uncorrelated between Run I and Run II periods.
- The uncertainties in the *Backgrounds estimated from theory (BGMC)* category are taken to be 100% correlated among all measurements in the same channel.
- The uncertainties in the *Backgrounds estimated from data (BGData)* category are taken to be 100% correlated among all measurements in the same channel and same run period.
- The uncertainties in the *Model for b jets (bJES)*, *Out-of-cone correction (cJES)*, *Light-jet response (1) (rJES)* and *Signal modeling (Signal)* categories are taken to be 100% correlated among all measurements.

Table II: The matrix of correlation coefficients used to determine the combination of the CDF top-quark mass.

CDF Preliminary
Correlations between the input top-qark mass measurements

	Run I published			Run II published			Run II preliminary	
	ℓ+jets	$\ell\ell$	alljets	ℓ+jets	L_{XY}	MET	$\ell\ell$	alljets
CDF-I ℓ+jets	1.00	0.29	0.32	0.49	0.07	0.26	0.54	0.27
CDF-I $\ell\ell$	0.29	1.00	0.19	0.29	0.04	0.16	0.32	0.17
CDF-I alljets	0.32	0.19	1.00	0.30	0.04	0.16	0.37	0.18
CDF-II ℓ+jets	0.49	0.29	0.30	1.00	0.08	0.32	0.52	0.30
CDF-II L_{XY}	0.07	0.04	0.04	0.08	1.00	0.04	0.06	0.04
CDF-II MET	0.26	0.16	0.16	0.32	0.04	1.00	0.29	0.18
CDF-II $\ell\ell$	0.54	0.32	0.37	0.52	0.06	0.29	1.00	0.32
CDF-II alljets	0.27	0.17	0.18	0.30	0.04	0.18	0.32	1.00

Using the inputs from Table I and the correlations specified here, the resulting matrix of total correlation coefficients is given in Table II.

The measurements are combined using a program implementing two independent methods: a numerical χ^2 minimization and the analytic best linear unbiased estimator (BLUE) method [27, 28]. It has been checked that they give identical results for the combination. The BLUE method yields the decomposition of the uncertainty on the CDF M_{t} combination in terms of the uncertainty categories specified for the input measurements [28].

V. RESULTS

The resultant combined value for the top-quark mass is

$$M_{\mathrm{t}} = 173.20 \pm 0.57\,(\mathrm{stat}) \pm 0.74\,(\mathrm{syst})\ \mathrm{GeV}/c^2.$$

Adding the statistical and systematic uncertainties in quadrature yields a total uncertainty of 0.93 GeV$/c^2$, corresponding to a relative precision of 0.54% on the top-quark mass. It has a χ^2 of 5.6 for 7 degrees of freedom, corresponding to a probability of 58%, indicating good agreement among all input measurements. The breakdown of the uncertainties is shown in Table III. The total statistical and systematic uncertainties are reduced relative to the Winter 2011 combination [12] and the published combination [15] due to the increase of the CDF data samples in the $\ell\ell$ and alljets analyses.

The pull and weight for each of the inputs, as obtained from the combination with the BLUE method, are listed in Table IV. The input measurements and the resulting CDF mass of the top quark are summarized in Fig. 1.

The weights of some of the measurements are negative, which occurs if the correlation between two measurements is larger than the ratio of their total uncertainties. In these instances the less precise measurement will acquire a negative weight. While a weight of zero means that a particular input is effectively ignored in the combination, channels with a negative weight affect the resulting M_{t} central value and help reduce the total uncertainty [27]. To visualize the weight each measurement carries in the combination, Fig. 2 shows the absolute values of the weight of each measurement divided by the sum of the absolute values of the weights of all input measurements. Negative weights are represented by bins with a different (grey) color. We note, that due to

Table III: Summary of the M_{t} uncertainties from the combination procedure. The categories are described in the text. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature.

CDF Preliminary
Combined M_{t} uncertainties

	Uncertainty in [GeV/c^2]
In situ light-jet calibration (iJES)	0.44
Response to $b/q/g$ jets (aJES)	0.08
Model for b jets (bJES)	0.13
Out-of-cone correction (cJES)	0.01
Light-jet response (2) (dJES)	0.07
Light-jet response (1) (rJES)	0.22
Lepton modeling (LepPt)	0.01
Signal modeling (Signal)	0.46
b-tag modeling (btag)	0.04
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.13
Calibration method (Method)	0.14
Multiple interactions model (MHI)	0.11
Systematic uncertainty (syst)	0.73
Statistical uncertainty (stat)	0.57
Total uncertainty	0.93

Table IV: The pull and weight for each of the inputs, as obtained from the combination with the BLUE method to determine the combination of the top quark mass.

CDF Preliminary
Pulls and the weights of M_{t} measurements

	Run I published			Run II published			Run II preliminary	
	ℓ+jets	$\ell\ell$	alljets	ℓ+jets	L_{XY}	MET	$\ell\ell$	alljets
Pull	+0.40	−0.51	+1.12	+0.50	−0.67	+0.48	−0.76	+1.11
Weight [%]	−4.7	−1.1	−1.0	+79.2	+0.4	+15.5	−3.0	+14.8

correlations between the uncertainties the relative weights of the different input channels may be significantly different from what one could expect from the total accuracy of each measurement as represented by error bars in Fig. 1.

No input has an anomalously large pull. It is, however, still interesting to determine the top-quark mass separately in the alljets, ℓ+jets, $\ell\ell$, and MET channels (leaving out the L_{XY} measurement). We use the same methodology, inputs, uncertainty categories, and correlations as described above, but fit the four physical observables, $M_{\mathrm{t}}^{\mathrm{alljets}}$, $M_{\mathrm{t}}^{\ell+\mathrm{jets}}$, $M_{\mathrm{t}}^{\ell\ell}$, and $M_{\mathrm{t}}^{\mathrm{MET}}$ separately. The results of these combinations are shown in Fig. 3 and Table V.

Using the results of Table V we calculate the following χ^2 values including correlations: $\chi^2(\ell+\mathrm{jets}-\ell\ell) = 1.56/1$, $\chi^2(\ell+\mathrm{jets}-\mathrm{alljets}) = 1.66/1$, $\chi^2(\ell+\mathrm{jets}-\mathrm{MET}) = 0.38/1$, $\chi^2(\ell\ell-\mathrm{alljets}) = 3.67/1$, $\chi^2(\ell\ell-\mathrm{MET}) = 2.03/1$, and $\chi^2(\mathrm{alljets}-\mathrm{MET}) = 0.30/1$. These correspond to chi-squared probabilities of 22%, 20%, 54%, 6%, 15%, and 58% respectively, indicating that the top-quark mass determined in each decay channel is consistent in all cases.

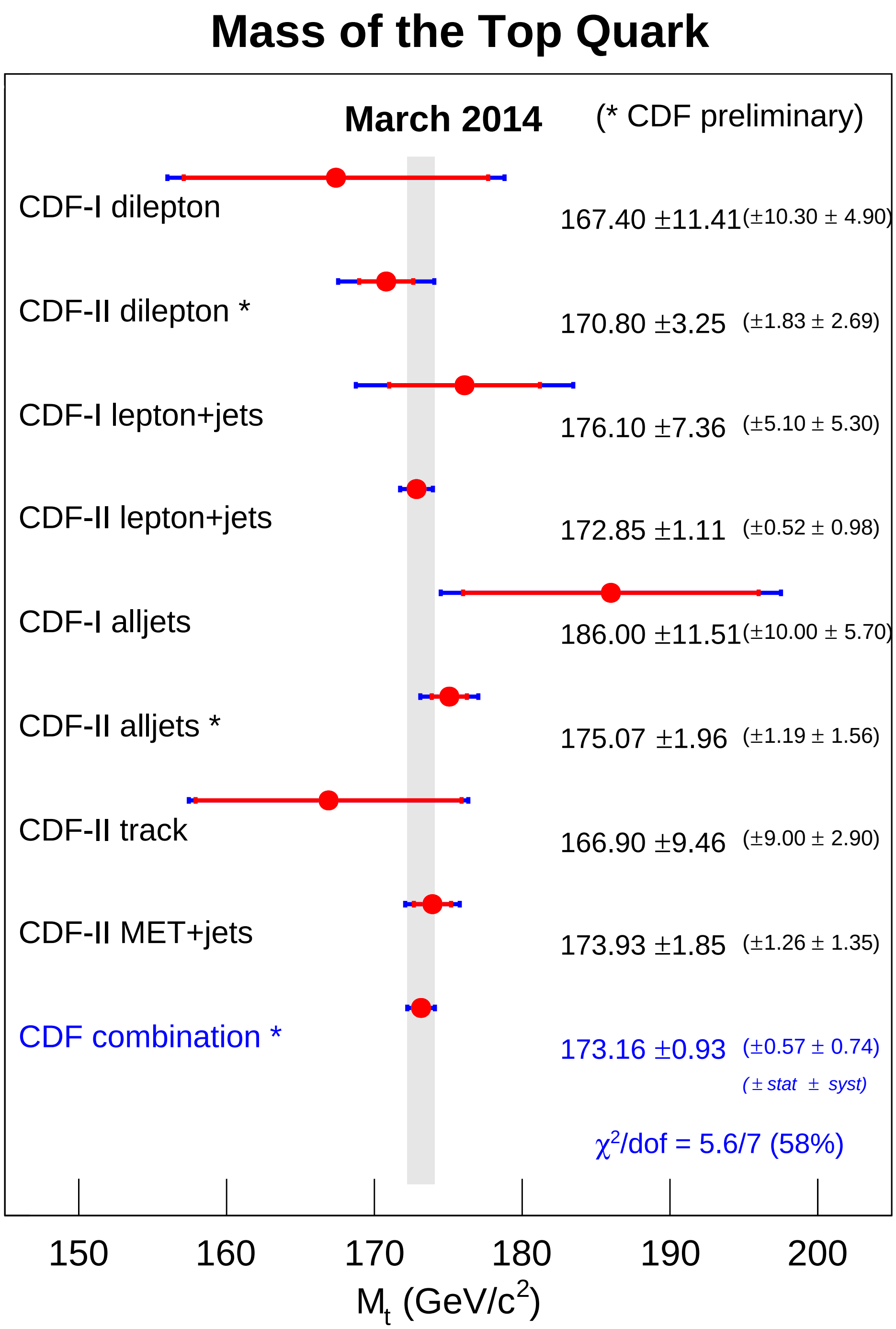

Figure 1: Summary of the input measurements and resulting CDF combination of the top-quark mass.

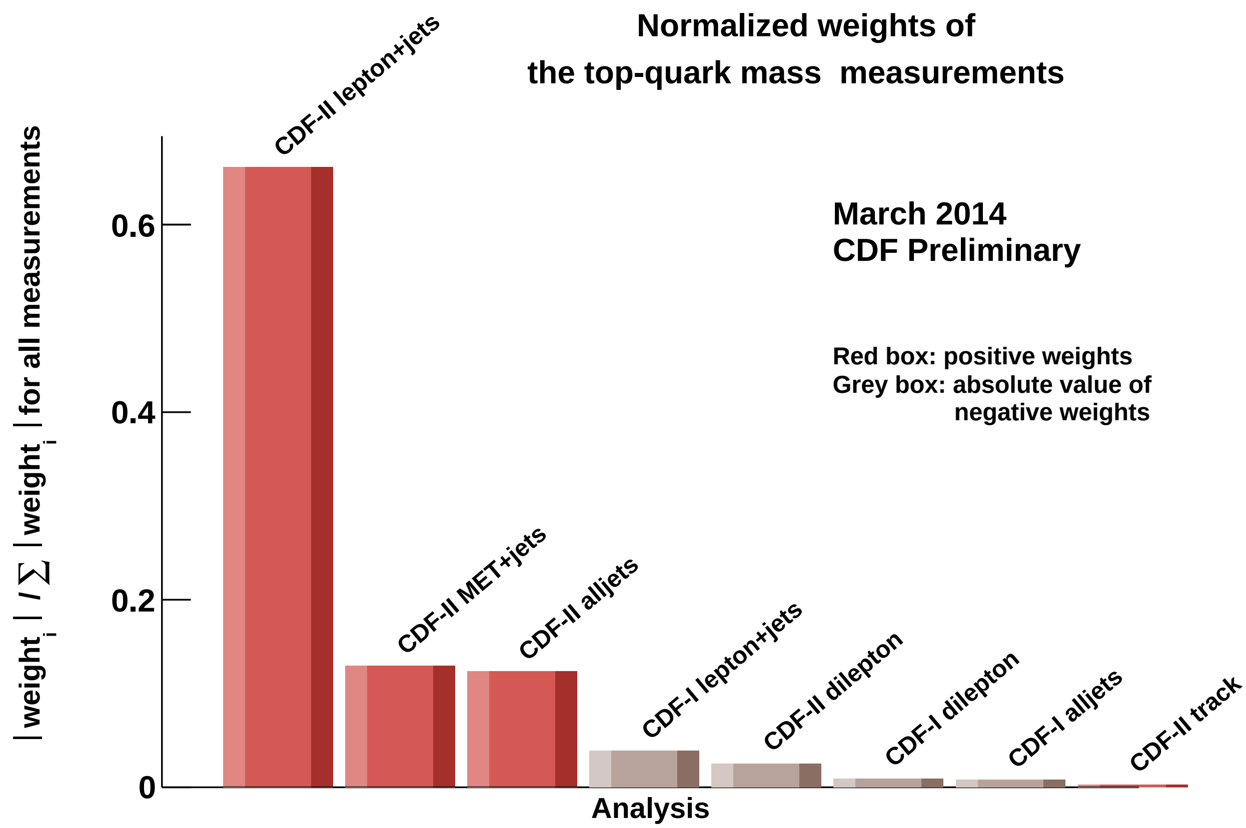

Figure 2: Relative weights of the input measurements in the combination. The relative weights have been obtained by dividing the absolute value of each measurement weight by the sum over all measurements of the absolute values of the weights. Negative weights are represented by their absolute value, but using a grey color.

Table V: Summary of the combination of the 8 measurements by CDF and in terms of four physical quantities, the mass of the top quark in the alljets, ℓ+jets, $\ell\ell$, and MET decay channels.

CDF Preliminary

Final State	M_{t} [GeV/c^2]	Correlations			
		$M_{\mathrm{t}}^{\ell+\mathrm{jets}}$	$M_{\mathrm{t}}^{\ell\ell}$	$M_{\mathrm{t}}^{\mathrm{alljets}}$	$M_{\mathrm{t}}^{\mathrm{MET}}$
$M_{\mathrm{t}}^{\ell+\mathrm{jets}}$	172.51 ± 1.02	1.00			
$M_{\mathrm{t}}^{\ell\ell}$	169.40 ± 2.76	0.40	1.00		
$M_{\mathrm{t}}^{\mathrm{alljets}}$	174.99 ± 1.90	0.25	0.26	1.00	
$M_{\mathrm{t}}^{\mathrm{MET}}$	173.64 ± 1.79	0.25	0.20	0.13	1.00

To test the influence of the choices in modeling the correlations, we performed a cross-check by changing all non-diagonal correlation coefficients of the correlation matrix defined in Section IV from 100% to 50%, except for the statistical and *In situ* light-jet calibration (iJES) uncertainties, and re-evaluated the combination. The result of this large variation of degree of correlation is a $+0.10$ GeV/c^2 shift of the top-quark mass and increases by 0.01 GeV/c^2 the total uncertainty. Next, we changed all non-diagonal correlation coefficients (0% or 100%) to 50%, again, except for the statistical and *In situ* light-jet calibration (iJES) uncertainties. For this case the

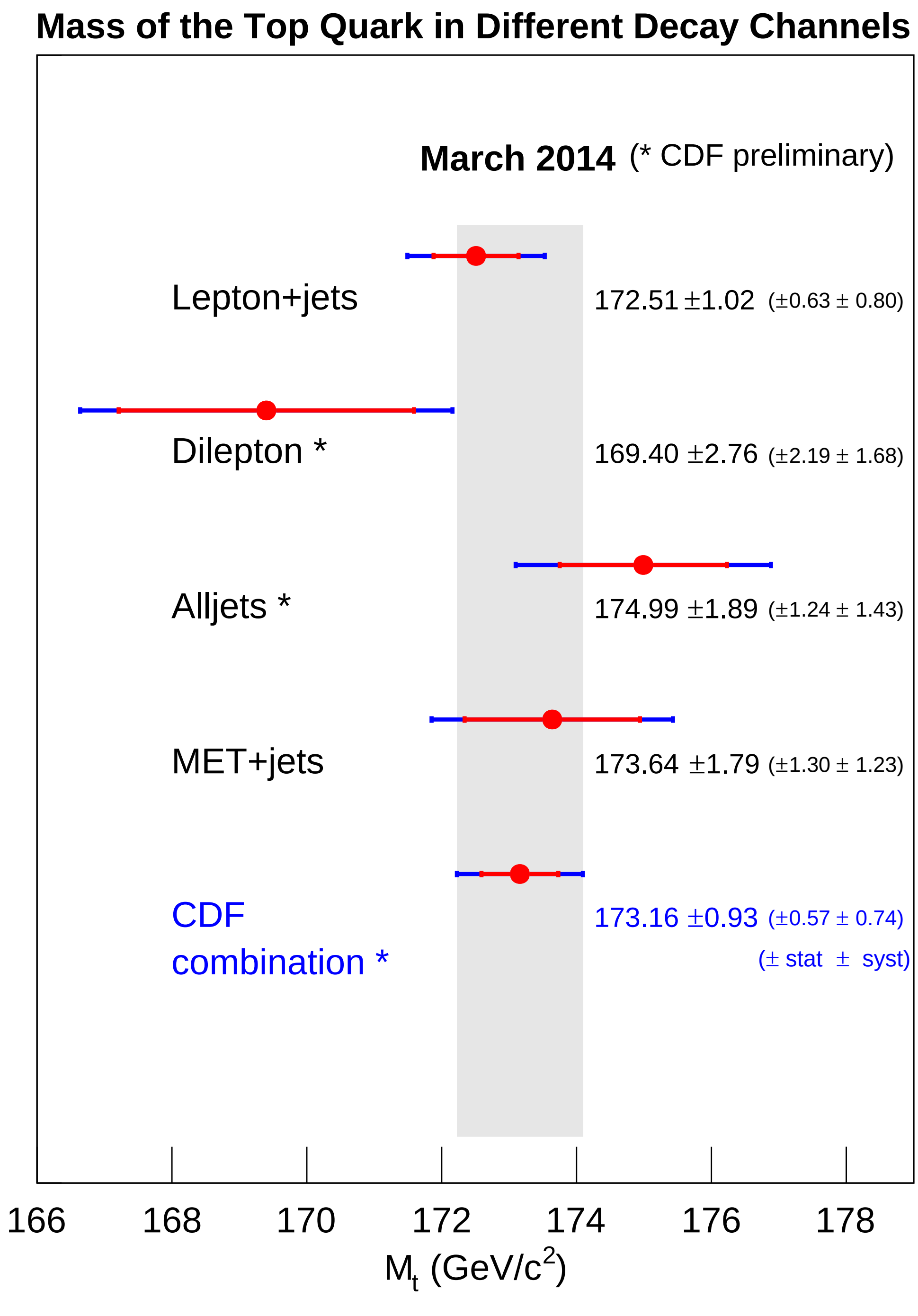

Figure 3: Summary of the combination of the 8 top-quark measurements by CDF for different final states.

combination procedure returns a $+0.015$ GeV/c^2 shift of the top-quark mass and increases the total uncertainty by 0.03 GeV/c^2. The chosen approach is therefore showing a good stability and consistency.

VI. SUMMARY

The final combination of measurements of the mass of the top quark from the CDF experiment has been presented. These measurements are performed on the full CDF datasets available. This combination includes three published Run I measurements, three published Run II measurements, and two preliminary Run II measurements. Taking into account the statistical and systematic uncertainties and their correlations, the preliminary result for the CDF combination is $M_{\rm t} = 173.16 \pm 0.57\,(\rm stat) \pm 0.74\,(\rm syst)$ GeV/c^2, where the total uncertainty is obtained assuming Gaussian systematic uncertainties. The central value is $0.46\,\rm GeV/c^2$ higher than our March 2011 average [12] of $M_{\rm t} = 172.70 \pm 1.09\,\rm GeV/c^2$. Adding in quadrature the statistical and systematic uncertainties yields a total uncertainty of 0.93 GeV/c^2 which represents an improvement of 16%.

The mass of the top quark is now known with a relative precision of 0.54%, limited by the systematic uncertainties, which are dominated by the jet energy scale uncertainty. This is the final result from CDF and it is not expected to be updated in the further.

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